

THE NON-CAUSAL ORIGIN OF THE BLACK HOLE–GALAXY SCALING RELATIONS

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ABSTRACT

We show that the $M_{\text{BH}}-M_{\text{bulge}}$ scaling relations observed from the local to the high- z Universe can be largely or even *entirely* explained by a non-causal origin, i.e. they do not imply the need for any physically coupled growth of black hole and bulge mass, for example through feedback by active galactic nuclei (AGN). Provided some physics for the absolute normalisation, the creation of the scaling relations can be fully explained by the hierarchical assembly of black hole and stellar mass through galaxy merging, from an initially uncorrelated distribution of BH and stellar masses in the early Universe. We show this with a suite of dark matter halo merger trees for which we make assumptions about (uncorrelated) black hole and stellar mass values at early cosmic times. We then follow the halos in the presence of global star formation and black hole accretion recipes that (i) work without any coupling of the two properties per individual galaxy and (ii) correctly reproduce the observed star formation and black hole accretion rate density in the Universe. With disk-to-bulge conversion in mergers included, our simulations even create the observed slope of ~ 1.1 for the $M_{\text{BH}}-M_{\text{bulge}}$ -relation at $z = 0$. This also implies that AGN feedback is not a required (though still a possible) ingredient in galaxy evolution. In light of this, other mechanisms that can be invoked to truncate star formation in massive galaxies are equally justified.

Subject headings: galaxies: fundamental parameters — galaxies: nuclei — galaxies: bulges — galaxies: evolution

1. INTRODUCTION

About a decade ago tight correlations between galaxy properties and those of central supermassive black holes (BHs) were empirically established: BH masses scale with the luminosity, the mass and the velocity dispersion of their host galaxies' bulges (Magorrian et al. 1998; Ferrarese & Merrit 2000; Gebhardt et al. 2000; Tremaine et al. 2002; McLure & Dunlop 2002; Marconi & Hunt 2003; Häring & Rix 2004; Gültekin et al. 2009; Jahnke et al. 2009; Merloni et al. 2010). These correlations were quickly interpreted to yield two important implications: (i) If these correlations were to exist for a random set of galaxies, then every galaxy should contain a supermassive BH (e.g. Kormendy & Richstone 1995) (ii) If every galaxy contains a BH and given the observed scaling relations, the evolution of galactic bulges and central BHs should be coupled by a physical mechanism (the 'co-evolution' picture).

The former statement appears to be true at least above some mass threshold, and introduced a new ingredient, the central BH, in galaxy evolution. The latter statement is based on the vast energy available from accreting black holes, providing the easiest conceivable mechanism to physically couple BH and bulge properties despite the difference in linear scales. Coupling only a few percent of this energy in an "AGN feedback" (Silk & Rees 1998) to the gas within the galaxy would have vast implications on the temperature and structure of the surrounding interstellar medium. Ad hoc models (Granato et al. 2004; Di Matteo et al. 2005; Croton et al. 2006) were very successful in generating feedback loops that involve the energy from AGNs for quenching star formation (SF) and

fueling of the AGN themselves. Different incarnations of AGN feedback are in principle able to not only couple SF and BH accretion, but to simultaneously fix a number of existing problems in galaxy evolution, namely an overproduction of massive galaxies in semi-analytic models as well as the inability to truncate SF fast enough to reproduce the observed color-magnitude bimodality of galaxies (Baldry et al. 2004). This motivated the inclusion of AGN feedback in a yet-to-be-determined form and physical description as the driving force behind the BH–bulge scaling relations.

Although the actual effectiveness and impact of at least "quasar mode" feedback models is still unclear, the interpretation of the scaling relations as a physically coupled evolution is largely assumed to be correct and continues to provide the basis for many studies. As an example, the evolution of the scaling relations (Treu et al. 2004; Peng et al. 2006a,b; Treu et al. 2007; Schramm et al. 2008; Jahnke et al. 2009; Merloni et al. 2010; Bennert et al. 2010; Decarli et al. 2010) is investigated in order to constrain the physical drivers behind co-evolution and the growth mechanisms of BHs.

1.1. An alternative origin of the scaling relations

Peng (2007) demonstrated a thought experiment for the potential origin of a $M_{\text{BH}}-M_{\text{bulge}}$ -relation without a physical coupling, but as the result of a statistical convergence process. In short, he showed that in principle, arbitrary distributions of M_{BH}/M_* -ratios in the early universe converge towards a linear relation through the process of galaxy merging. In this central-limit-theorem view, a large number of mergers will average out the extreme values of M_{BH}/M_* towards the ensemble average. What was deliberately left open in this experiment was whether there are enough major galaxy mergers in the history of an actual galaxy in order to drive this process

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far enough.

In this present study we pick up this thought by following realistic ensembles of dark matter halos through cosmic time. Our immediate aim is to test whether the simple assembly of galaxies and their BHs according to a Λ CDM merger tree is able to produce BH–galaxy scaling relations from initial conditions at early times, where M_{BH} and M_{bulge} (or M_*) were completely uncorrelated per individual galaxy. We circumvent the inherent problems and degrees of freedom of a full semi-analytic model by not trying to simultaneously solve the problem of SF truncation or correct BH or stellar mass function, but restrict the question solely to the genesis of the scaling relations. As an input for SF and BH accretion we use observed relations, but prevent any recipes that im- or explicitly couple BH and stellar mass growth *per individual galaxy*.

2. NUMERICAL SIMULATIONS AND MERGER TREES

In this paper we use the Lagrangian code PINOCCHIO (Monaco et al. 2002) to construct high resolution Λ CDM merger trees (for a comparison between Nbody codes and PINOCCHIO see Li et al. 2007). The simulation has a box size of 100 Mpc, and 1500^3 particles, this ensures a very high mass resolution, $m_p = 1.01 \times 10^7 M_\odot$. The construction of merger trees is straightforward with PINOCCHIO: the code outputs a halo mass every time a merger occurs, i.e., when a halo with more than 10 particles merges with another halo. From an initial 6.5×10^6 halos, we receive a resulting sample of 10932 halos with $M > 10^{11} M_\odot$ at $z = 0$.

When two halos merge, the less massive one can either survive and continue to orbit within the potential well of the larger halo until $z = 0$, or merge with the central object. The averaging process described above will only apply to this second category of halos (the ones that actually merge), we then adopt the dynamical friction formula presented in Boylan-Kolchin et al. (2008) to compute the fate of a halo. The orbital parameters of the halo are extracted from suitable distributions that reproduce the results of Nbody simulations as described in Monaco et al. (2007). If the dynamical friction time is less than the Hubble time at that redshift, we consider the halo to merge at a time $t = t_{\text{dyn}}$, if it is longer the satellite halo is removed from our catalog. Each halo in our sample at $z = 0$ has formed by at least 200 mergers and the most massive ones have had more than 5×10^4 encounters.

3. CREATING SCALING RELATIONS: AVERAGING AND MASS FUNCTION BUILD UP BY HIERARCHICAL MERGING

The main message of this work is to demonstrate which effect merging over cosmic time has on an ensemble of halos with initially uncorrelated M_{BH} and M_* values. These values change their distribution and converge towards a linear relation by $z = 0$ – in the absence of SF, BH accretion, disk-to-bulge conversion and hence any physical connection between the two masses.

For this task we follow dark matter halos through their assembly chain. We assign a stellar and a BH mass to each dark matter halo once its mass becomes larger

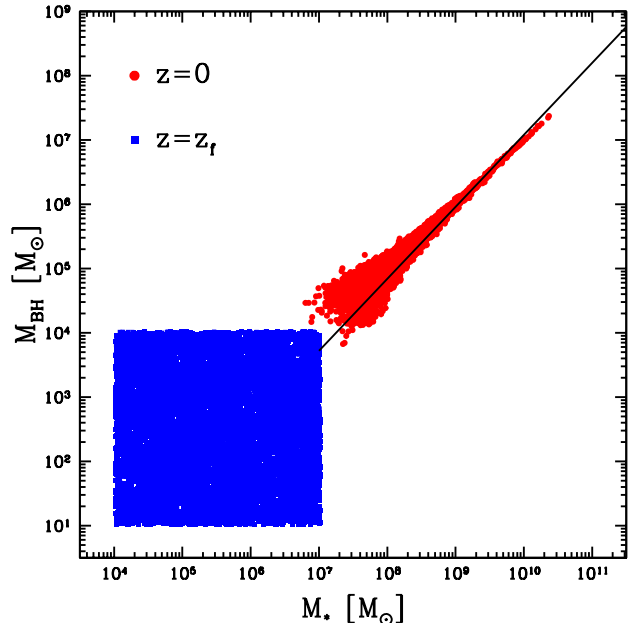


FIG. 1.— Changes of M_{BH} vs. M_* from an initially uncorrelated (within 4 dex in each parameter) distribution at high z (blue points) to $z = 0$ purely by mass assembly along the merger trees, i.e. without SF, BH accretion and disk-to-bulge mass conversion. A very tight correlation of slope 1.0 is created by the merging, with smaller scatter for higher masses which experienced more merger. The black line is the observed local $M_{\text{BH}}-M_*$ -relation from Häring & Rix (2004) with slope=1.12.

than $10^8 M_\odot^2$, the corresponding redshift in the following is called z_f . We set our initial guesses for M_* and M_{BH} as a fixed fraction of the dark matter mass plus a (large) random scatter. We used $M_*/M_{\text{dm}} = 10^{-3}$ and $M_{\text{BH}}/M_{\text{DM}} = 10^{-7}$ for the initial ratio; the scatter is taken from a logarithmically flat distribution of 3 dex for the two quantities (blue squares in Figs. 1 and 2).

We have no knowledge of any realistic seed mass scatter, but take 4 orders of magnitude variations in the M_{BH}/M_* -ratio as a proxy for “uncorrelated”. Empirical constraints on the possible parameter space for seed black hole mass do not seem to support seeds more massive than $\sim 10^5 M_\odot$ (Volonteri & Natarajan 2009), towards lower masses a few solar mass BHs are clearly being produced by stars. Whether this matches the true distribution of seed masses is not important, but by simply taking a large range that is currently not ruled out represents a rather conservative starting point for our demonstration. Halos are then propagated along the merger tree to $z = 0$ (the red points in Figs. 1 and 2). When two halos merge according to our dynamical friction formula, we set the resulting stellar and BH masses equal to the sum of the individual masses before the merger (Volonteri et al. 2003). The final mass in M_{BH} and M_* as well as the corresponding normalization is determined simply by the sum of the individual halos contributing to a final halo.

Fig. 1 shows that the hierarchical formation of galaxies

² We picked this mass since at lower masses halos likely did/do not form stars at all (Macciò et al. 2010). The most massive progenitor of $z = 0$ galaxies form according to this definition in the range $z = 15 - 17$, while low mass satellites can form as late as $z \sim 3$.

provides a strong inherent driver from the uncorrelated initial distribution to a linear relation³. This effect is independent of the chosen initial conditions as Figure 2 demonstrates, where completely different initial conditions result in a relation with the same slope and very similar scatter.

This experiment shows that the dominating structural parts of the observed $M_{\text{BH}}-M_*$ -scaling relation – i.e. (1) the existence of such a correlation, (2) that it extends over several orders of magnitude in mass, (3) the fact that the slope is near unity, and (4) an increasing scatter to lower masses – can be explained by this physics-, feedback- and coupling-free process. A slope ~ 1 scaling relation does not need any physical interaction of galaxy and black hole. In the next sections we will show that this holds also when adding “2nd order” effects like actual star formation and black hole accretion, as well as disk–bulge conversion.

4. ADDING STAR FORMATION, BLACK HOLE ACCRETION, AND DISK-TO-BULGE CONVERSION

We so far demonstrated that merging alone is the basic mechanism to create a $M_{\text{BH}}-M_*$ scaling relation. However we need to add a number of ingredients to our model: Placing all mass already at high redshift is not conservative, since all of stellar and BH mass is subject to the full merger averaging process. In the actual universe we know that the majority of BH and stellar mass in the universe was created after $z \sim 6$ (Soltan 1982; Hopkins & Beacom 2006), and hence experiences less merger generations. Moreover pure merging produces a monotonic relation between M_{DM} and M_* as shown in the upper panel of Figure 3, which is at odds from empirical results. Since SF and BH accretion density depend on redshift, we will add the approximate right amount of SF and BH growth at the right cosmic times, and thus at the right place in time with respect to the merger cascade. The goal of this exercise is not to create a full semi-analytic model of galaxy formation, but to test which effect realistic assumptions about mass growth have on the resulting $M_{\text{BH}}-M_*$ scaling relation.

To construct SF and BH accretion recipes we will use three observed relations as input: (i) The halo occupation distribution, i.e. the relation between dark matter halo mass M_{DM} and M_* (Moster et al. 2010), (ii) the Lilly-Madau relation for the evolution of SF rate (Hopkins & Beacom 2006), and (iii) the evolution of bolometric luminosity of AGN (Hopkins et al. 2007).

We want to explicitly note that by using these relations, we do not force any coupling of M_{BH} and M_* or M_{bulge} *per individual galaxy*, but all recipes only relate to ensemble averages. Any potential implicit couplings only act on the ensemble and not on an individual galaxy, hence they can not induce a correlation in the (originally uncorrelated) data points.

4.1. Star Formation

³ The convergence is in fact too strong (see next sections), as the scaling relation it produces by $z = 0$ is much tighter than the observed 0.3 dex scatter. In principle the scatter has a \sqrt{N} dependency on the number N of merger generations, but the relation gets complicated by the different masses of the merging components and different merging times across the tree.

Up to now, at redshift $z = 0$ the stellar mass of our galaxies is simply given by the sum of all stellar masses of its j -progenitors $M_*^0(i) = \sum M_*(z_f)(j)$, masses that as explained were originally drawn from a random distribution. As shown in the upper panel of Fig. 3, for a given halo mass the stellar mass obtained in this way is too low when compared to the empirical expectations from Halo Occupation Distribution (HOD) models (e.g. Moster et al. 2010). This is because the total galaxy is more than the sum of its seeds and we have neglected star formation so far. On the other hand, Fig. 3 tells us exactly how much stellar mass each halo is missing. Hence we take this constraint, the HOD results, to fix the stellar mass produced through star formation:

$$M_{\text{SF}}^*(i) = M^*(M_{\text{dm}}(i)) - M_0^*(i) \quad (1)$$

where $M^*(M_{\text{dm}}(i))$ is the expected stellar mass for the i -th halo with dark matter mass $M_{\text{dm}}(i)$ as predicted by the HOD model presented in Moster et al. (2010).

Now we need to distribute this stellar mass from SF along time, i.e. among all progenitors of galaxy i along the merger tree. We do that according to the following formula that gives the stellar mass produced through SF for the j -th halo in the merger tree of final i halo:

$$M_j^{\text{SF}} = A \times M_*^q(j) \times LT(j) \times f(z_f(j), z_m(j)). \quad (2)$$

The constant A is fixed by the requirement that $M^{\text{SF}}(i) = \sum_j M_j^{\text{SF}}$ and is the same for all progenitors. The time LT is the lifetime of a halo, defined as time between the formation redshift (z_f : when $M_{\text{DM}} > 10^8 M_\odot$) and the moment z_m , when it merges with a more massive halo, which is not necessarily the main branch of the merger tree. With this definition we assume that galaxies are able to actively form stars only when they are the central object within their host halo.

The function f is used to give different weights to the life time LT at high and low redshift, in this way, for a given life time, a galaxy will produce more (less) stars at high (low) redshift, according to the Lilly-Madau plot⁴. We define $f(z_1, z_2)$ as the integral between z_1 and z_2 of the assumed star formation rate (SFR):

$$f(z_1, z_2) = \int_{z_1}^{z_2} \text{SFR}(z) dz. \quad (3)$$

In our reference model we assume for the redshift evolution of the SFR the functional form suggested by Hopkins & Beacom (2006), namely results listed in Table 1 for a modified Salpeter IMF (see Hopkins & Beacom 2006, for more details). Finally the factor $M_*^q(i)$ takes care of the observed mass-dependence of specific star formation rates and we fixed the exponent $q = 0.8$ (e.g. Daddi et al. 2007; Bouche et al. 2009). In the Appendix A we will present results for different choices for q and $\text{SFR}(z)$.

Let us summarize one more time our parametrization for star formation: When the j halo appears at $z_f(j)$ it gets an initial stellar mass ($M_*(z_f)(j)$) from a random distribution as described in Section 3. Then it will “produce” its own stars (M_j^{SF}) until it will be accreted onto,

⁴ We note that we do not include a different shape of this star formation history as a function of mass. As the Appendix shows, this will not have any effect on the results

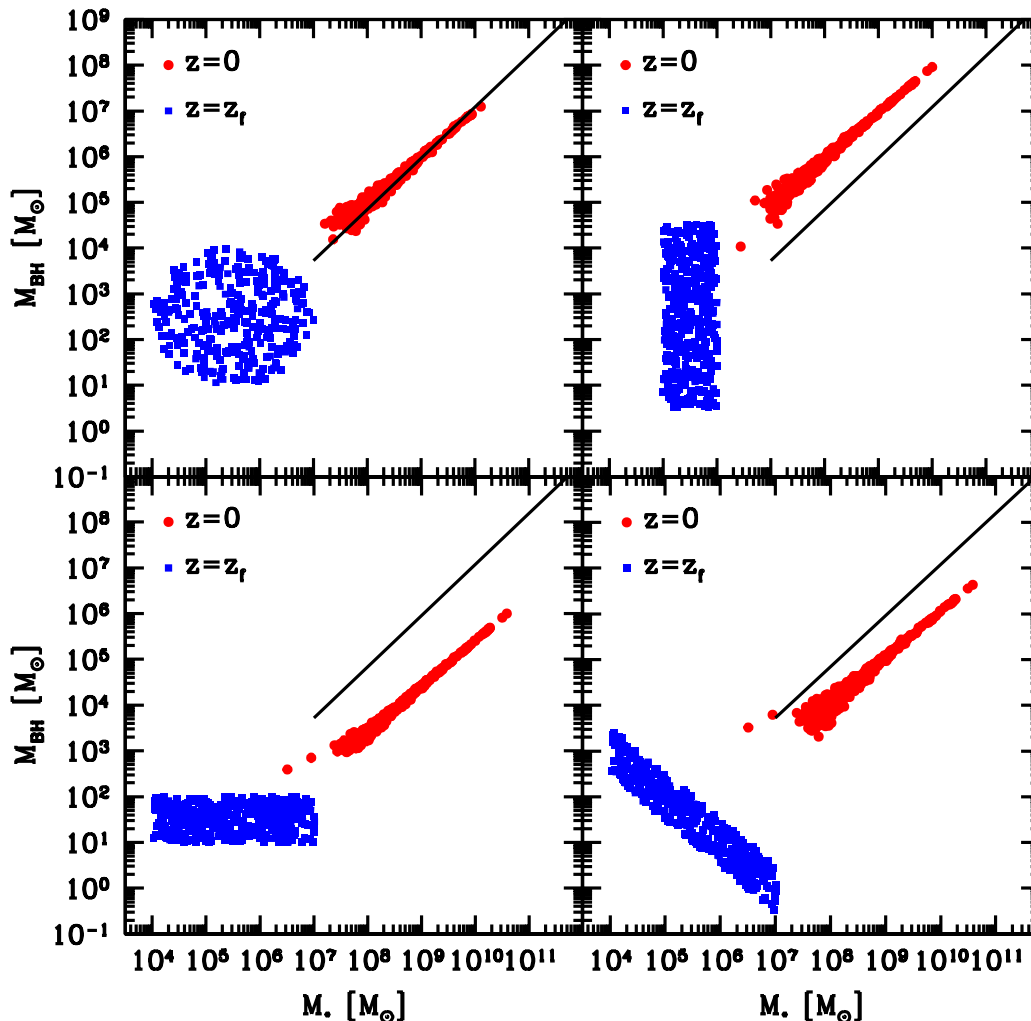


FIG. 2.— The scaling relations are produced independently of the initial conditions: Shown are four vastly different initial conditions – for a subset of our halos for better visibility –, all leading to a slope=1 relation at $z=0$ with similar scatter. The $z=0$ normalisation comes out differently since the geometric mean of the initial masses is different (flat distribution in logarithm for both quantities). Symbols and the line have the meaning as in Figure 1.

and become part of, a more massive halo. During its lifetime it will also accrete stellar mass from merging (lower) mass haloes. If halo j will merge with the central galaxy it will add a fraction of its stellar mass to the bulge of the central galaxy as described below in Section 4.2. If halo j will merge with a more massive halo (k) before merging with the central halo it will give all its stellar mass to halo k and cease to exist as a halo of its own.

4.2. Disk to bulge conversion

We assume that all stellar mass produced through star formation will occur in the disk component of each halo and then apply a recipe to convert part of this disk mass to bulge mass as a consequence of mergers.

The amount of disk-to-bulge mass conversion depends on a multitude of parameters as mass ratio, gas fraction, and orbital parameters of the merger, which are impossible to implement in our context. Instead we follow a simpler recipe inspired by the numerical results of Hopkins et al. (2009), solely depending on the stellar

mass ratio of the two merging partners: (i) Bulge mass of main halo and satellite will just be co-added, (ii) the disk mass of the satellite fully goes into the resulting bulge, and (iii) a fraction of the main halo disk, directly proportional to the mass ratio, also gets converted into bulge mass. With this recipe we are able to approximately reproduce the ratio of bulge to total mass observed in the local universe.

4.3. Black hole accretion

Since the mechanisms of BH accretion continue to be unclear, we assume a simple recipe; the BH will double its mass in a stochastic way on a characteristic time scale τ . This will happen for all j progenitors of halo i . Similar to what we have done for star formation, we link the number of doublings of a given halo to its life time and we weight this time with a function g similar to the function f in Section 4.1.

In practice the number of mass doublings of the j -th

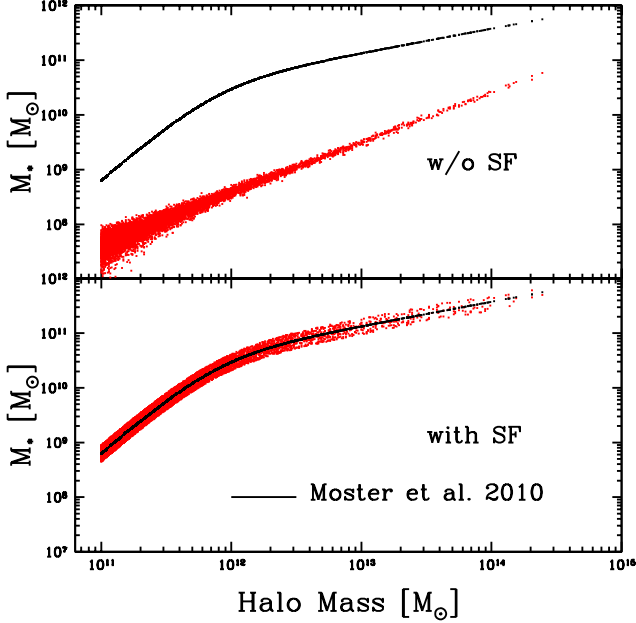


FIG. 3.— The relation between M_* and M_{DM} at $z = 0$. The black line shows the predictions from Moster et al. (2010), the red point the results from our simulations. Upper: Only merging but no SF taken into account. Lower: With our SF recipe implemented.

black hole in the i merger tree is given by the expression:

$$N_{\text{doub},j} = LT(j) \times g(z_f(j), z_m(j)) / \tau, \quad (4)$$

Where LT has the same meaning as in Eq. 2. For black hole accretion we choose as the weighting function $g(z_1 : z_2)$ the integral between z_1 and z_2 of the bolometric luminosity of AGN ($AGN_L(z)$):

$$g(z_1, z_2) = \int_{z_1}^{z_2} AGN_L(z) dz. \quad (5)$$

In our reference model the redshift evolution of the AGN bolometric luminosity is modeled with a double power law aimed to reproduce the results of Hopkins et al. (2007, Figure 8):

$$\log \left(\frac{AGN_L(z)}{L_{\odot} \text{Mpc}^{-3}} \right) = \begin{cases} 2.02 \cdot \log(z) + 7.83 & \text{for } z < 1.7 \\ -2.09 \cdot \log(z) + 8.78 & \text{for } z \geq 1.7 \end{cases} \quad (6)$$

Similarly to the f function, g can be used to allow for higher accretion rates at high redshift compared to low redshift for a fixed halo life time.

The characteristic time τ is chosen in order to match the normalization of the observed $M_{\text{BH}}-M_{\text{bulge}}$ -scaling relation at $z = 0$ for $\log(M_{\text{BH}}) = 7$ and we obtained $\tau = 1.9 \times 10^9$ Gyrs. As a stochastic element to BH growth we cast for each of the $N_{\text{doub},j}$ events a random number from a flat distributing in the range $[0:1]$ and effectively double the BH mass only if this random number is > 0.5 . For the main branch the number of doublings is of the order of 6–8, while it is in the range 0–3 in the other branches of the tree. In the Appendix A we will present results for different choices of the parameters involved in equation 4.

4.4. Resulting scaling relations

The $M_{\text{bulge}}-M_{\text{BH}}$ -distribution at $z = 0$ with the above recipes added is shown in Figure 4, with the observed values overplotted. Compared to the pure merger assembly in Figures 1 and 2 we note a substantially increased scatter – closer to the observed – and a steeper than linear relation. Still, despite both the shift of SF and BH growth to later times as well as the random parts of SF and BH accretion, a clear correlation is produced. The effects of SF, BH accretion and disk-to-bulge conversion do not destroy the correlations but only induce a “2nd order” modification of them. Over time a mass function is built up and the scatter decreases substantially from the initial 4 dex, particularly for the $\log(M_{\text{bulge}}) > 10$ regime.

The simulated relation is very similar to the observed points, it reproduces the slope > 1 almost perfectly, even the fact that at the high mass end the observed points lie above the mean slope – and this without adjustable parameters beyond normalization. Also, the higher scatter at low masses can be seen in both simulations and observations, the “cloud” above the $z = 0$ relation in our model data represents disk galaxies with small bulge masses as observed by Greene et al. (2008). As can be seen in Figure A.4 in the Appendix, these objects would still lie on the local mass scaling relation, but with their total and not their bulge mass.

We want to stress that the results in Figure 4 do not depend on our parametrization of SF rate or BH accretion. For example changing the functional form of f or g in Eqs. 2 and 4 only marginally affects the scatter of the simulated $M_{\text{BH}}-M_{\text{bulge}}$ -relation and leaves the slope unchanged. The same is true for the other parameters described in the previous sections, see the Appendix for details. There is a sole exception to this, the assumed initial seeding masses: The larger the initial M_{BH} and M_* , the less mass has to be created by SF and BH accretion. In this way less mass is entering the halos at later times and more mass is subject to the full cascade of mergers, which will lead to a smaller scatter in the scaling relations at $z = 0$.

5. DISCUSSION

We showed above that all basic properties of the BH–bulge mass scaling relation in the local Universe – a relation between properties of individual galaxies – are produced naturally by the merger-driven assembly of bulge and BH mass, and without any coupling of SF and BH mass growth per individual galaxy.

The convergence power of galaxy merging is very strong for a realistic halo merger history, even with a correct placement of SF and BH accretion along cosmic time. This means that the mechanism Peng (2007) sketched in his thought experiment works also in a realistic Universe – there is enough merging occurring in the universe and hence (most of) the scaling relations can be entirely explained without any physical mechanisms that directly couples M_{bulge} and M_{BH} growth for a given object.

5.1. Implicit coupling of black hole and galaxy?

The scaling relations are produced naturally in our toy model – but does this preclude any implicit coupling of M_{BH} and M_* by design? The most obvious features to be

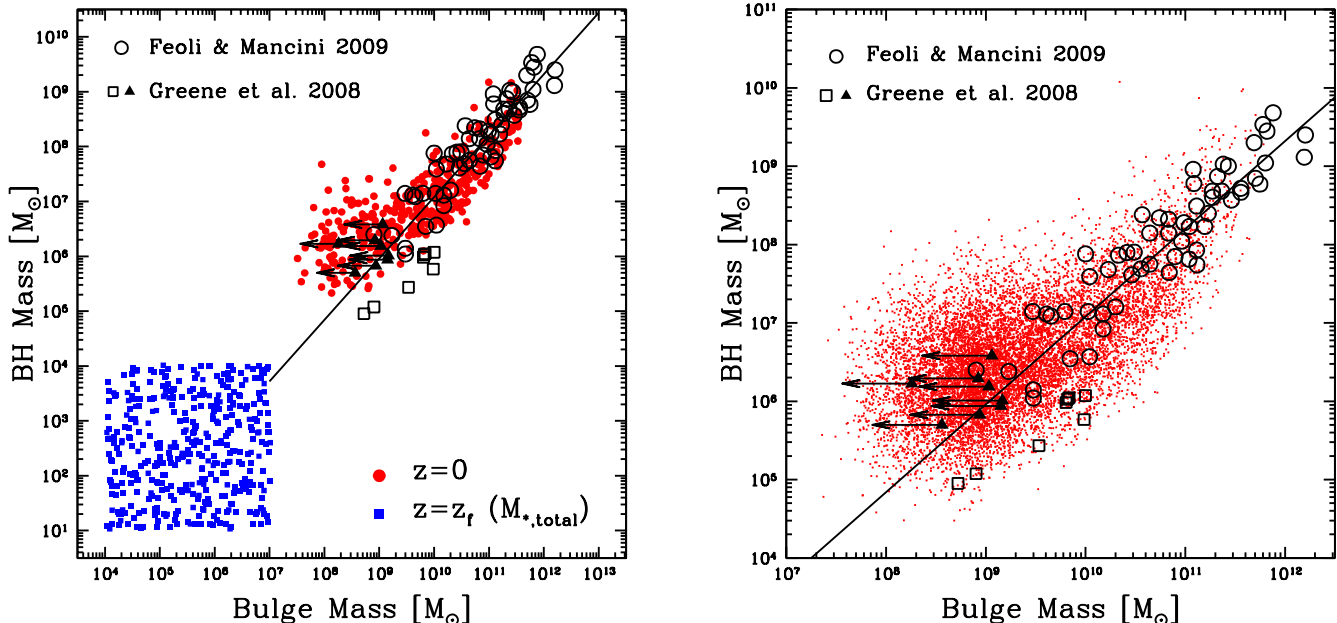


FIG. 4.— Left: Initial uncorrelated high redshift seeds for M_* and M_{BH} (blue filled squares) and resulting $z = 0$ $M_{\text{BH}}-M_{\text{bulge}}$ scaling relation for a subset of 400 randomly selected merger trees (red points), compared to the observed local relation in black, including the compilation from (Feoli & Mancini 2009, circles), low-mass spheroids (open squares) and upper limits for spiral bulges (triangles) from Greene et al. (2008). The solid line is the linear fit by Häring & Rix (2004) with a slope of 1.12. Right: The full set of resulting 10932 galaxies at $z = 0$ with the low- z data overlotted.

discussed in this respect are (a) the shape of the halo occupation distribution and (b) the question, which mechanism determines the relative value of BH accretion to SF, hence the absolute normalisation of the $M_{\text{BH}}-M_{\text{bulge}}$ -relation.

(a) HOD shape: The HOD was empirically inferred and shows that the ratio of stellar to dark matter mass is not constant but is a function of mass itself. Towards the massive end stellar mass does not increase in parallel to DM, star formation appears suppressed. Its impact on the $M_{\text{BH}}-M_{\text{bulge}}$ -relation is the slight curvature in Figure 4 with the noticeable upturn at the massive end – consistent with the observations. The HOD shape represents a long known feature of galaxy formation and was “fixed” in models by introduction of a quenching mechanism, suppressing SF above some mass, often by inclusion of AGN feedback recipes.

In our toy model however, we do not make specific assumptions about which mechanism produces the HOD we use as a constraint. We do not tie BH accretion or a merger event to the suppression of SF – it can be suppressed by any mechanism, e.g. a modified SN feedback recipe or gravitational heating by infalling clumps of matter. The latter mechanisms are completely independent of BH accretion and, while modifying the HOD, by nature can not have an impact on the $M_{\text{BH}}-M_{\text{bulge}}$ -relation. Even if AGN feedback was the source for shaping the HOD, this would only be the cause of the second order shape deviation from a linear slope, not the existence of the $M_{\text{BH}}-M_{\text{bulge}}$ -relation itself.

(b) Absolute normalisation: Our initial model just propagates the (rather ad hoc) seed masses in stars and BH to $z = 0$, i.e. the normalisation of the $M_{\text{BH}}-M_{\text{bulge}}$ -relation at $z = 0$ is directly set by the ensemble mean ratio of seed masses. Since most of stellar and BH mass

in reality is produced by SF and BH accretion later on, the high- z ratio is in fact unconnected to the $z = 0$ normalisation.

In our simulation we set the normalisation by requesting a match of our simulation results with the empirical $M_{\text{BH}}-M_{\text{bulge}}$ -relation at $M_* = 10^{10} M_{\odot}$. Arguments have been brought forward that the actual normalisation must be the result of a regulatory feedback loop involving BH accretion and SF. This is an attractive scenario, as it would explain both the creation of the scaling relations as well as their normalisation. Models of this kind have been implemented in several semianalytic models of galaxy formation, in all cases with free parameters that actually control the absolute normalisation of the resulting scaling relations, set to ad hoc values to again match this and other observations. Since we show in this paper that (most aspects of) the $M_{\text{BH}}-M_{\text{bulge}}$ -scaling relations are created automatically by hierarchical assembly, these feedback models actually seem to achieve too much – the creation of a certain M_{BH}/M_* ratio for *each galaxy* and at all times, which as a conspiracy would come on top of the formation path of the scaling relations demonstrated here.

This said, we want to sketch the outline of an alternative scenario, that could well be responsible for the absolute normalisation but has not yet been explored: The main ingredients for both SF and BH accretion are (i) gas, and (ii) a trigger to form stars or to bring down gas to the BH. For both stars and BHs the amount of growth is basically a product of the two ingredients. At early times gas was ample and the number of both galaxy mergers and gas disk instabilities was high until the peak of activity around $z = 2$. The triggering mechanisms subsequently decreased with the decreasing number of mergers and reduced gas reservoirs, either in

number or duration or both. If both SF and BH accretion were to be ruled by a set of random triggering mechanisms and the specific gas fraction in a galaxy, then very high- z galaxies might exhibit a strong variance in their M_{BH}/M_* -distribution as well as in their (instantaneous and also time averaged) BH accretion over SF ratio, with a dependency on the actual total mass, morphology, gas mass, trigger type, environment, etc. However, as a cosmic mean there will be a *global* M_{BH}/M_* value, just as an average over the efficiency of the spectrum of random triggering mechanisms and realised conditions to produce new stars or BH mass – a number which could also change with time.

The hierarchical assembly of galaxies and its averaging mechanism now relieves us from having to search for regulatory mechanism *per galaxy*, since with each galaxy merger the spectrum of M_{BH}/M_* values will increasingly average out. The fact that the slowly starting depletion of gas reservoirs in galaxies at $z \sim 2$ is accompanied with, and not preceded by, a slowly decreasing merger rate has the consequence that at higher redshifts there were enough mergers to average out the extreme M_{BH}/M_* systems – at lower z , with a decaying gas reservoir and merger rate and the transition to a “secular universe” (see e.g. Cisternas et al. 2011), the prerequisites for producing new extreme values become less and less frequently fulfilled. The ensemble converges towards the observed $M_{\text{BH}}-M_{\text{bulge}}$ -relation at $z = 0$.

Recently, first nested multi-scale simulations of gas inflow into the very centers of galaxies have been successful (Hopkins & Quataert 2010) and give a first impression of how in principle random instabilities, strongly depending on the actual conditions in the galaxy, can create gas inflow into the very center and the fuelling of either BH, SF or both. It is mechanisms of this kind that will create a certain mean value of M_{BH}/M_* averaged over all galaxies, which can be vastly different for an individual galaxy. How different is so far unclear, and whether this mechanism for BH fuelling precludes “runaway” growth of BHs to 100- or 1000-fold in a single instance, though unlikely, needs to be seen. All of this can in principle be realized without any AGN feedback – though it does not rule it out –, and has the freedom to have a mass- or environmental-dependent efficiency component, as we also observe a non-unity slope of the $z = 0$ scaling relation.

Coming back to the initial question, we conclude that there is no necessity that our toy model makes any implicit assumptions about a physical $M_{\text{BH}}-M_*$ -coupling.

5.2. Further consequences of this mechanism

Our mechanism is also able to explain other observational results that are often used as evidence to support the picture of agn feedback.

(a) One of them is the potentially different $M_{\text{BH}}-M_{\text{bulge}}$ -relations in galaxies with classical and pseudo-bulges (Greene et al. 2008; Gadotti & Kauffmann 2009). Pseudo-bulges are thought to be formed through secular processes, rather than major merging (Kormendy & Kennicutt 2004). This has the immediate implication that the bulge has taken a different long- or mid-term assembly route compared to the BH, hence it is actually not expected that galaxies with pseudo-bulges obey the same $M_{\text{BH}}-M_{\text{bulge}}$ -relation than those with

classical ones.

(b) Hopkins et al. (2009) found that the stellar mass inside a very small radius near the black hole $M_*(< R)$, comparable to the BH’s sphere of influence, shows a much larger scatter than the scatter in M_{BH}/M_* . They argue that this is an indication that gas was transported to near the BH, to form said stars, but that this had apparently no impact on the scatter in M_{BH} , hence a self regulating mechanism should have been at work.

With our model also this can be simply explained: The BH and bulge of a galaxy take part in the same long-term assembly and averaging cascade, hence their values correlate and scatter in their ratio is small. The central density of stars on the other hand does not. It is governed by more short term gas inflow, star formation and redistribution mechanisms, hence it is expected that it does not correlate well with the overall mass of the bulge or the BH.

(c) Following this line of argument, we in principle expect a correlation with M_{BH} for any (mass) parameter that is subject to the same Λ CDM assembly chain. This includes the halo mass, to some extent the total mass of the galaxy (for both see Appendix B and Figure A.4), but also e.g. the total mass of globular clusters in a galaxy, which recently has been found empirically by Burkert & Tremaine (2010).

(d) On the other hand, our model is too basic to be able to reproduce higher order effects. A number of studies (Aller & Richstone 2007; Hopkins et al. 2007; Feoli & Mancini 2009; Feoli et al. 2010) have suggested that the most fundamental relation with M_{BH} is neither M_{bulge} nor σ_{bulge} but that rather galaxy binding energy or potential well depth.

What these studies actually find are residual correlations in the scaling relations that are in some way related to the compactness of a bulge/spheroid at a given M_{BH} . This can be effective radius or binding energy or any other quantity that is ex- or implicitly a measure of compactness. Since bulge mass depends just linearly on the progenitor mass ratios, the exact size, compactness, binding energy of a spheroid produced in a merger will depend non-linearly on other parameters like gas fraction, merger orbit, etc. These parameters could easily be responsible for the residual correlation found in the $M_{\text{BH}}-M_{\text{bulge}}$ -relation as they are measures of the specific short- or mid-term merger history of each galaxy, while M_{bulge} is a long term integral. Our deliberately simple toy model itself can not make any statements on this issue as it does not trace e.g. galaxy scale radii.

Interpreting the above points with respect to the relevance of AGN feedback, we find no strong argument for AGN feedback as a *necessary* mechanism at work. However this does not mean that AGN feedback does not exist. It only means that AGN feedback is still a *possible* mechanism involved in parts of galaxy evolution, which might be important e.g. for subclasses of the galaxy population⁵. This implies that other proposed means of energy (or momentum) injection that have been proposed to quench SF in massive galaxies (e.g. Dekel & Birnboim

⁵ Undoubtedly, at least “radio mode” feedback (Croton et al. 2006) is actually observed in some massive clusters (e.g. Fabian et al. 2006; Best et al. 2006) and possibly on the group-level (Giodini et al. 2010).

2006; Khochfar & Ostriker 2008; Lo Faro et al. 2009) are viable options. In other words, all other mechanisms that can be invoked to truncate star formation in massive galaxies appear to be equally justified.

5.3. The comparison with previous work

Our result is different to all previous studies, and with more than a decade of semianalytic models including BHs having passed, one of the obvious questions is: Why have others not found this before? The closest studies to ours is a short proceedings contribution by Gaskell (2010), which is basically paraphrasing Peng (2007), and the work by Hirschmann et al. (2010). Their study is a very systematic assessment of how the scaling relation scatter evolves under the influence of galaxy merging. However, their initial setup in all cases was an existing correlation of M_{BH} and M_* , and due to their specific goal they deliberately ignored the influence from SF and BH accretion.

Other recent studies investigating this subject either explicitly include AGN feedback (e.g. Croton et al. 2006; Robertson et al. 2006; Booth & Schaye 2009; Johansson et al. 2009; Shankar et al. 2009) or couple the merging scenario with a self regulation prescription for BH growth (e.g. Kauffmann & Haehnelt 2000; Volonteri & Natarajan 2009). In retrospect it is quite obvious why they did not find our results earlier, as most of these models were developed for galaxy evolution in general. Once BHs entered the equations, they added terms of (regulated) BH growth and, when evaluating the generated $M_{\text{BH}}-M_{\text{bulge}}$ -relations, noted that their prescription managed to produce a decent match to the empirical relation. The interpretation that this meant the AGN feedback- or coupling-prescription were correct, now requires re-evaluation from our new point of view – it was the simple result of hierarchical assembly at work.

5.4. Impact on evolution studies

In the last decade a substantial number of attempts were made to measure local and higher redshift scaling relations of $M_{\text{BH}}-M_{\text{bulge}}$, $M_{\text{BH}}-\sigma_{\text{bulge}}$, or $M_{\text{BH}}-L_{\text{bulge}}$ (Treu et al. 2004; Peng et al. 2006a,b; Woo et al. 2006; Treu et al. 2007; Schramm et al. 2008; Jahnke et al. 2009; Merloni et al. 2010; Bennert et al. 2010; Decarli et al. 2010) and to interpret them with respect to the mechanisms that couple BH growth and their impact on galaxy formation. Which implications does the non-causal origin of the scaling relations have for these results? If the mean cosmic M_* and M_{BH} actually evolved similarly, our results explain at least a part of the *bulge* scaling relation evolution for galaxies with substantial disk components: it is the simple conversion of disk to bulge mass in galaxy mergers. What still remains interesting and needs to be substantiated is how at high redshifts the relation between M_{BH} and total M_* (or even M_{bulge} for bulge dominated galaxies) evolves (e.g. Walter et al. 2004). This would continue to predict a substantial early BH growth – with corresponding implications for BH feeding models.

One other aspect that could serve as a diagnostic is the evolution of the scaling relation scatter. When coupled with predictions of BH and stellar mass assembly from a proper model, the scatter can be used to study e.g. the distribution of seed M_{BH} at early times. We will follow up on this issue in a future publication.

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APPENDIX

TESTING THE MODEL: ARE THE PARAMETER CHOICES SPECIAL?

Few (free) parameters enter in our parametrization of star formation, black hole accretion and bulge to disk conversion. In this section we want to explore different choices with respect to our reference model and test their impact on the final results. All different models are listed in Table 1.

Figure A.1 shows the effect of varying our ‘weighting’ functions. In model B we set $SFR(z) = 1.0$, e.g. we assume a constant star formation rate as a function of redshift; in model C we set also $AGN_L(z) = 1.0$. The resulting $M_{BH}-M_{bulge}$ -relations are indistinguishable from the original (A) model. The bottom right panel of figure A.1 (model D) shows an even tighter correlation between $M_{BH}-M_{bulge}$ with respect to our reference model. This is because in model D we remove the stochasticity in the BH mass doubling, forcing all BHs to double their mass every τ Gyrs. This increases the number of doublings in the merger tree branches with short life time, increasing the fraction of BH mass that is accreted through mergers and hence is subject to the central limit theorem.

In Figure A.2 we check the effect of our parametrization of dynamical friction (model E, where the dynamical friction time is multiplied by five) and of our disk-to-bulge conversion, assuming that a fraction of the disk mass proportional to the square-root (model F) or proportional to the square of the merger ratio is promoted into the disk (model G).

TABLE 1
MODEL PARAMETERS

Model ^a	SFR(z) ^b	q ^c	AGN _L (z) ^d	Stochasticity ^e	B/D conversion ^f	Dynamical Friction ^g
A	HB06	0.8	H07	Y	M_{G1}/M_{G2}	B08
B	const.	0.8	H07	Y	M_{G1}/M_{G2}	B08
C	const.	0.8	const.	Y	M_{G1}/M_{G2}	B08
D	HB06	0.8	H07	N	M_{G1}/M_{G2}	B08
E	HB06	0.8	H07	Y	M_{G1}/M_{G2}	B08 × 5
F	HB06	0.8	H07	Y	$(M_{G1}/M_{G2})^{1/2}$	B08
G	HB06	0.8	H07	Y	$(M_{G1}/M_{G2})^2$	B08
H	HB06	1.0	H07	Y	M_{G1}/M_{G2}	B08
I	HB06	2.0	H07	Y	M_{G1}/M_{G2}	B08
L	HB06	3.5	H07	Y	M_{G1}/M_{G2}	B08

NOTE. — Parameter of reference (A) and test models (B–L). Values in bold face are differences to the reference model.

^a Results shown in Figures A.1, A.2 and A.3

^b Redshift dependent SFR; HB06 refers to Hopkins & Beacom (2006)

^c Exponent of mass dependence in SFR (see Eq. 2)

^d Redshift dependent AGN luminosity; H07 refers to Hopkins et al. (2007), Figure 8

^e Stochastic element in BH growth

^f Amount of dynamical friction in galaxy mergers; B08 refers to Boylan-Kolchin et al. (2008)

Finally, models H–L (Figure A.3) test the importance of a dependence of SFR on stellar mass. In these models we vary the q exponent in equation 2: models H and I do not show any appreciable variation when compared with model A. Model L which has an absolutely unrealistic value for q is the only model where we were able to break the $M_{bulge} - M_{BH}$ correlation. This result can be easily understand in the following way: if star formation is a too strong function of stellar mass, then the vast majority of stars will be formed in the main branch of the tree that hosts (by definition) the most massive progenitor of our galaxy. This implies that the bulk of stellar mass will not be subject to any averaging process and hence the central limit theorem does not apply. Moreover given the artificially high fraction of stars produced within the central galaxy, there will be no major merger, this explains why in model L we do not get any bulge more massive than $4 \times 10^{10} M_{\odot}$.

All other model are not distinguishable from the reference model A, this underlines one more time the convergence power of galaxy mergers and shows that the actual implementation of star formation, dynamical friction, BH accretion and bulge formation are only secondary effects.

SCALING RELATIONS WITH STELLAR MASS AND HALO MASS

Hierarchical assembly produces correlations between any two parameters that take part in this cascade. The main focus of this paper lies on the $M_{BH} - M_{bulge}$ -relation, but M_{BH} also correlates with total stellar mass and dark matter halo mass. This is shown in the two panels of Figure A.4, which include the receipes for BHA. The clearest and simplest correlation is the one with M_{DM} (right side), which in the simple framework of this toy model is very close to slope=1, with some scatter and no bending.

M_{BH} vs. total stellar mass (incl. SF receipe), as shown on the left side of Figure A.4 is at the massive end largely identical to the $M_{BH} - M_{bulge}$ -view, because most galaxies there will have had sufficient numbers of minor and major mergers in order to make them bulge dominated. At the low-mass end, the scatter is still larger than at high masses, due to the smaller number of (averaging) past mergers for each halo, but it is somewhat smaller than for bulge mass, since the extra random element from disk-to-bulge conversion is absent. This also explains the missing plume of seemingly high M_{BH} -systems at low masses visible in Figure 4, which in this way can be explained to actually be disk galaxies with small bulges and normal sized black holes for the amount of total stellar mass.

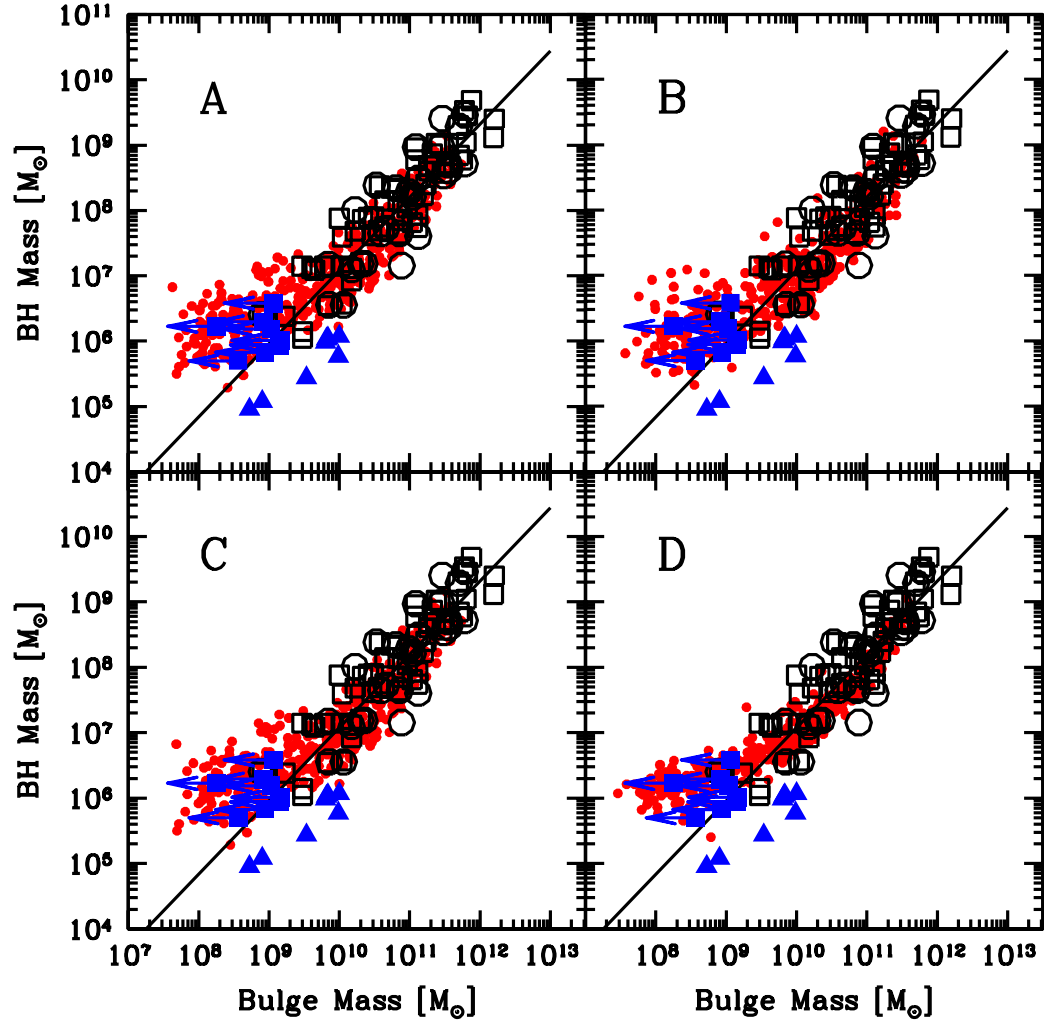


FIG. A.1.— Models A–D; see Table 1 for model parameters.

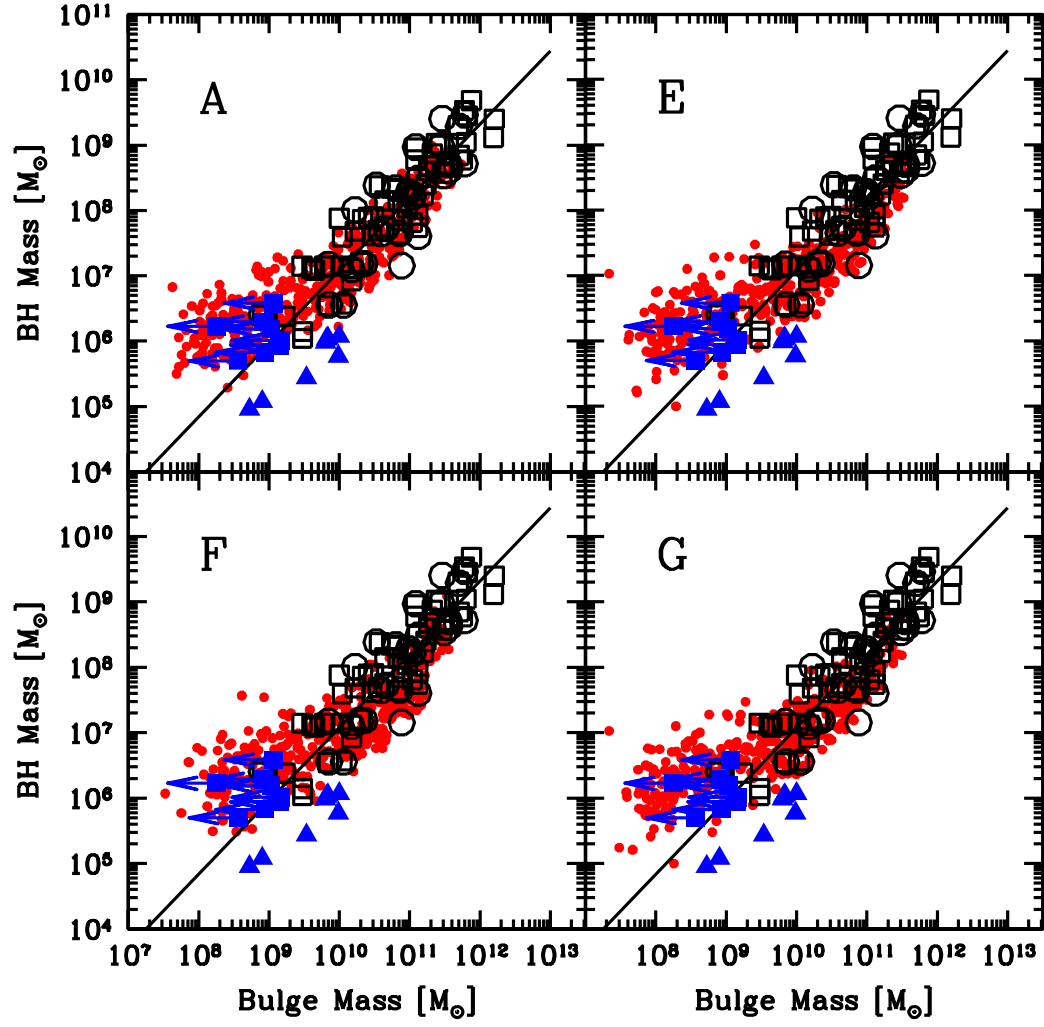


FIG. A.2.— Models E–G; see Table 1 for model parameters. The reference model A is shown again as a comparison.

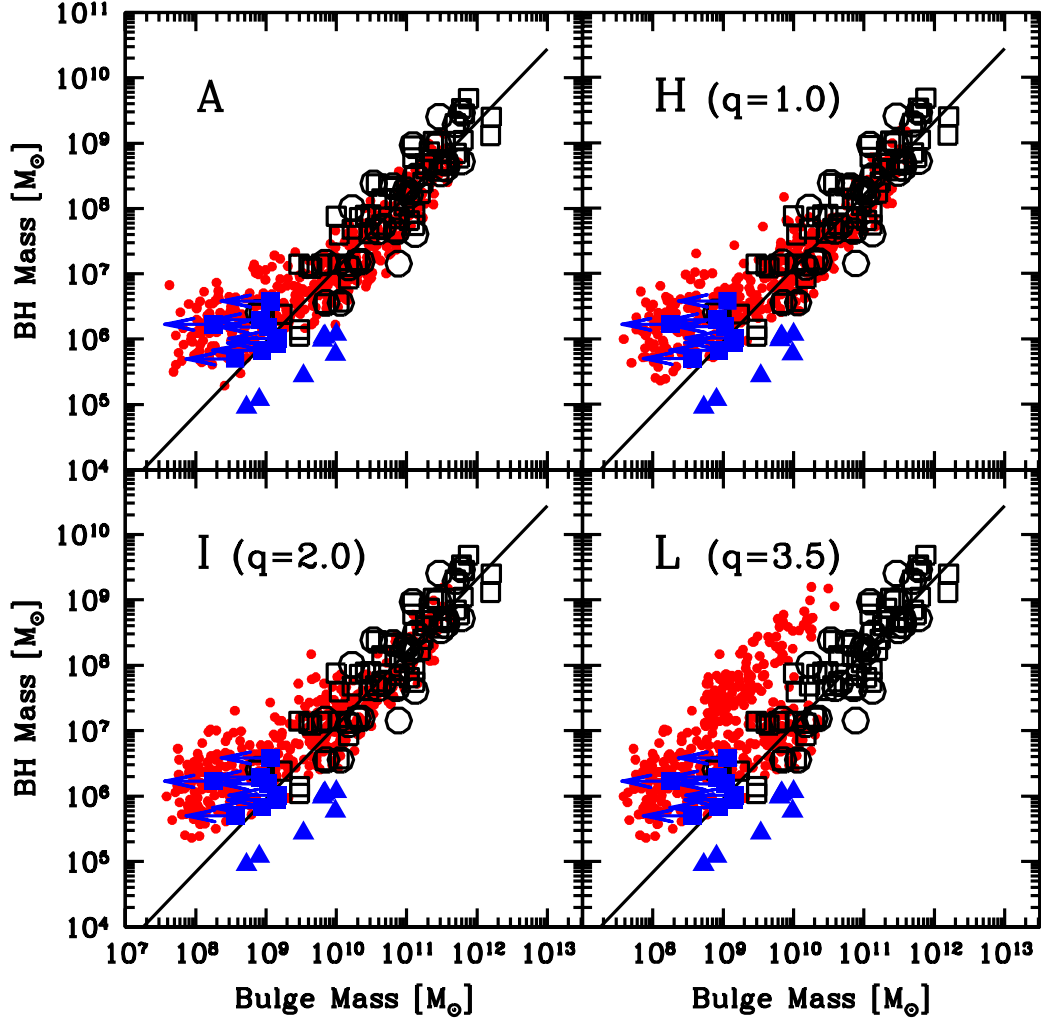


FIG. A.3.— Models H–L; see Table 1 for model parameters. The reference model A is shown again as a comparison.

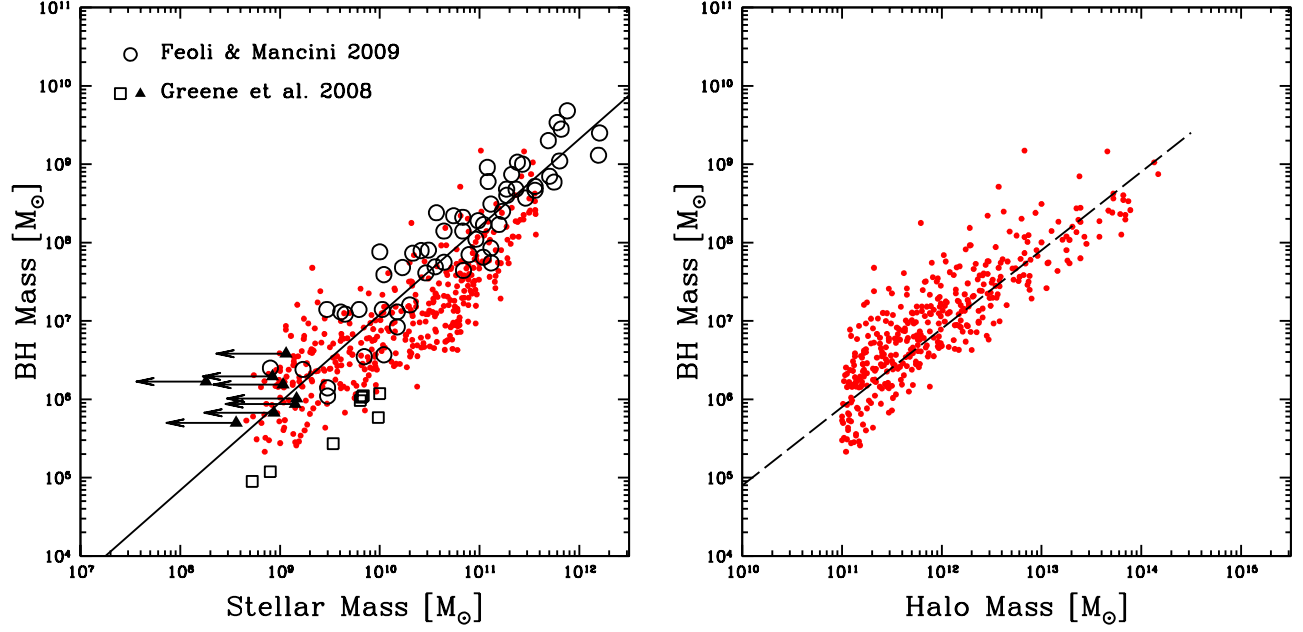


FIG. A.4.— Left: Black hole vs. total stellar mass for 400 of our model halos (red points), compared as in Figure 4 to the observed local relation in black, including the compilation from (Feoli & Mancini 2009, circles), low-mass spheroids (open squares) and upper limits for spiral bulges (triangles) from Greene et al. (2008). As before, the solid line is the linear fit by Häring & Rix (2004) with a slope of 1.12. Right: Black hole vs. dark matter halo mass. The dashed line with slope=1 is plotted to guide the eye. Please note: The abscissa is shifted by 3dex with respect to the stellar mass plot on the left.